

# Ducted Propeller Design and Verification for Contemporary Offshore Support Vessels

Anton Minchev<sup>1</sup>, Jens Ring Nielsen<sup>2</sup>, Ege Lundgren<sup>2</sup>

<sup>1</sup>FORCE Technology, Copenhagen, Denmark

<sup>2</sup>MAN Diesel, Frederikshavn, Denmark

## ABSTRACT

The paper presents the design approach for modern ducted propeller systems, primarily suited for Offshore Supply Vessels (OSV) as adopted and currently used by MAN Diesel. The various stages of the design process are presented and commented; the extensive use of CFD tools for design optimization is outlined; a case-study example is presented including results from model tests and full scale sea trials. The higher efficiency of the specially designed Alpha High Thrust (AHT) nozzle is demonstrated and verified by model test and sea trial results. Further possibilities of bollard pull (BP) increase were experimentally investigated, including variation of nozzle tilt and azimuth angle variations.

## Keywords

Offshore supply vessel  
Ducted propeller design  
Bollard pull testing  
CFD

## 1 INTRODUCTION

An OSV is characterized by a number of varying operating modes (straight supply to and from rigs, towage/anchor handling, dynamic positioning etc.) and requires a high degree of flexibility and redundancy. Most OSV's are highly powered and designed as twin screw vessels with ducted CP propellers in order to achieve the required BP and a high maneuverability. The other operating conditions seldom play a role in specifying the main engine power. However, the BP is not solely determined by the installed power but also by an optimized propulsion system and hull lines. Consequently, it pays off to take a holistic approach including all three items in the design loop.

## 2 DUCTED PROPELLER DESIGN PROCESS

The design of the propulsion system is generally carried out in two phases and supported with different optimization tools and computer codes.

### 2.1 Preliminary Design

The development of OSV's has for many years focused on achieving a certain required BP which in many cases

must be contractually guaranteed. The BP was previously recognized as being solely linked to the installed propulsion power. The industry has devised several rules of thumbs for determining the propulsion power needed to obtain the specified BP. All of them are related to the installed power and do not include the propulsion system or the hull design in the applied simplified formulas. One of these rules simply states that one will get a BP of 1.3 tons per 100 hp and does not reflect the importance of other parameters like propeller diameter, nozzle type, hull lines etc.

Applying those simplified rules often leads to higher installed powers compared to an approach where all elements are considered and optimized.

At MAN Diesel the calculation of the bollard pull and the needed power to obtain it is based on several factors which must be known beforehand either in case a BP must be calculated with a high accuracy or if the BP must be guaranteed.

- Maximum possible propeller diameter
- Type of nozzle (i.e. standard or high efficiency type) and L/D ratio
- Draft and immersion of propeller for calculating the influence of cavitation on the BP
- The structural support of the nozzle
- Rudder and shaft arrangement
- Aft ship lines and in particular the slope of the buttock lines

This information forms the basis for selecting and optimizing the propulsion system including main engine, reduction gear, propeller, nozzle and its arrangement. The proposed and quoted propulsion system will be optimized to reach the required BP, and will in most cases show less required power and higher propulsion efficiency compared to a traditional approach.

### 2.2 Detailed Design

The detailed design usually takes place after signing the contract when more information is available on the hull lines, engine, gearbox and shaft arrangement.

The following major issues could be briefly mentioned and commented here:

### 2.2.1 Aft ship hull form design

MAN Diesel makes a great deal of efforts to influence the design of the aft ship lines and the nozzle arrangement including its support.

The flow in the aft ship is highly complex and shows a pronounced viscous nature which requires a CFD calculation to analyze it in detail. However, several model tests have shown a distinct influence on the BP from the steepness of the buttock lines. The higher the slope of the buttock lines the lower the BP, mainly caused by an increase in the thrust deduction factor.

One item often forgotten in the design of the hull main parameters is the minimum draft that is needed to suppress air suction. The tendency towards larger propeller diameters combined with a low design draft has in some cases lead to air being sucked into the propeller with a detrimental effect on the BP. This tendency is most likely to occur in bollard pull condition or towing where the propeller loading is highest. Because the air suction phenomena is complex and depends on propeller loading and shaft immersion, this issue should form a part of the experimental verification of the shaft, propeller and nozzle design.

### 2.2.2 Propeller/Nozzle design

For years it has been common practice to design and optimize the propeller blades for each individual project but using more or less standard nozzle types. Since the early 1970's the 19A type nozzle has been applied universally for all sorts of purposes. The 19A originates from model tests carried out by MARIN (previously Wageningen) and is a simplified version of the 19 type nozzle in order to make it more production friendly. Recently MAN Diesel introduced a new nozzle type called Alpha High Thrust (AHT) that has been developed to improve the performance compared to standard types. The AHT nozzle is not a standardized design but customized according to its application i.e. L/D ratio and support type. As an example an AHTS vessel could be optimized for maximum BP, whereas a purse seiner could be optimized for service speed. The two nozzle designs will differ significantly not only in appearance, but also in performance when compared to a standard off-the-shelf design.

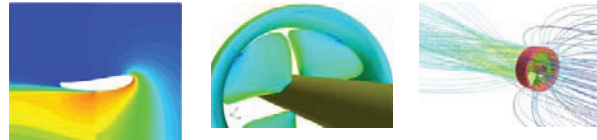


**Figure 1:** Comparison between 19A and AHT nozzle profile

CFD played an important role in the optimisation and development of the AHT nozzle. By systematically designing various nozzle geometries and subsequently perform CFD calculations on each design proposal an optimised solution was established. Following factors

were investigated and compared with a 19A nozzle in order to reach an optimum design with regard to BP.

- Optimum pressure distribution at in- and outlet
- Propeller/nozzle interaction including tip flow
- L/D ratio that confirmed the increase in BP with increasing length
- Outlet diffuser angle
- Optimum axial location of the propeller in the nozzle



**Figure 2:** Example of results from CFD calculations showing from left to right velocity and pressure distribution and streamlines in BP condition

Further details can be found in (Jeppesen & Marinussen 2006) and (Nielsen et al 2005).

The application of the AHT nozzle on a large number of vessels has confirmed the calculation and model test results. On average an improvement in BP of 6-8 % related to the AHT nozzle alone have repeatable been observed. Further improvement can be achieved if an optimisation of all items as discussed in this paper is addressed.

One additional advantage of the AHT nozzle is the significant increase in astern BP. Some unpublished model test results have shown that the astern BP is improved by 20-25% compared to the 19A nozzle. This makes the new AHT nozzle more efficient when operating in dynamic position mode or during station keeping.

The AHT nozzle is designed with double curvature, both in- and outside as shown in figure 1 and is consequently more costly to manufacture. However, the performance benefits clearly outweigh the increased manufacturing costs therefore recently most ducted propellers are delivered as AHT types.

Last but not least, one of the most effective ways of maximizing the BP is not only to optimize the nozzle for BP but also the propeller blades. This issue is not part of the present paper because it is closely associated with the cavitation performance of the propeller but was properly addressed during the design process.

### 2.2.3 Shaft strut and nozzle/rudder support design

A part from improving the hydrodynamic performance the nozzle must also exhibit sufficient structural strength to prevent unwanted vibration. The nozzle is in close proximity to the one of the major excitation sources onboard the vessel – the propeller - and is subjected to the varying forces originating from cavitation and in-stationary propeller forces. Nozzles supports must be designed to withstand the forces and be able to transmit them into the hull structure. To avoid global vibrations of the nozzle the support must be designed to have a higher

natural frequency than the propeller first order excitation frequency.

Two different types of support are used by the industry

- **Strut option**  
The nozzle is supported by two or three struts that are formed as airfoil section to minimize resistance and reduce the struts influence on the nozzle performance. For a twin screw OSV the struts are usually made with one in the top and one connecting the inner side of the nozzle to the center skeg. In some cases where additional stiffness is required a third strut can be fitted between the shaft bossing and the lower part of the nozzle. The orientation of the struts must be optimized either using CFD or model tests to reduce the appendage drag.
- **Head-box**  
In cases where the nozzle is close to the hull surface the support is made as one box connecting the nozzle to the hull. To ensure a sufficient stiffness and a natural frequency higher than the propeller excitation frequency a FE calculation will usually lead to a wide head-box – typically covering 70-90 deg of the nozzle circumference.



**Figure 3:** Typical strut and head-box arrangement

Both variants formed a part of the testing scope and the results will be reported in the following.

### 3 DESIGN CASE STUDY

#### 3.1 AHTS Vessel and Propulsive Complex Particulars

The case study will include presentation of the design process and final propulsive complex optimization for a 120T Bollard Pull AHTS vessel. Main particulars of the vessel and the propulsive complex are presented in the tables below.

**Table 1:** Ship, main engine, gearbox, propeller and nozzle particulars

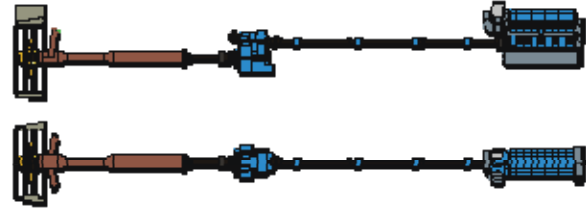
Ship Data		Engine and Gearbox data	
L <sub>OA</sub>	65.6 m	Engine	MAN 9L27/38
L <sub>PP</sub>	57.0 m	Power	3285 kW
B	16.0 m	Gearbox	MAN AMG55
T	5.7 m	Rev.	141 rpm

Propeller Data			Nozzle Data		
	Stock	Final		Stock	Final
D	3.80	3.80	D	3.80	3.80
Z	4	4	L/D	0.5	0.5
P/D <sub>0.7R</sub>	1.23	1.001	Type	NSMB19A	AHT
AE/A0	0.58	0.58			



**Figure 4:** Head-box (left) and strut (right) nozzle support arrangement



**Figure 5:** Propulsion plant arrangement

#### 3.2 Model Tank Testing

Model tank tests for OSV vessels are generally conducted to verify the propulsive performance with special emphasis on the bollard pull conditions. Initially the tests are conducted with available stock propeller/nozzle combinations, appropriately selected to match the geometrical characteristics of the anticipated final design propeller (diameter, blade area and pitch ratios, radial pitch distribution, etc.). Typically the stock nozzle has a standard NSMB19A section.

During the bollard pull test, the ship model is fixed to the towing carriage by a towing/pull force gauge, which directly measures the force interaction between ship model and carriage. The propeller revolutions are varied stepwise such that the propeller shaft power varies from about 40% to 100% of Maximum Continuous Rating (MCR). Measured quantities include: propeller(s) revolutions RPM, thrust(s)  $T_P$  and torque(s)  $Q$ , nozzle(s) thrust(s)  $T_N$  and total bollard pull  $T_{BP}$ . The difference between the BP and the sum of the measured thrusts (propeller + nozzle) accounts for the thrust deduction fraction, defined as:

$$t = 1 - \frac{T_{BP}}{\sum (T_P + T_N)} \quad (1)$$

The latter is widely used as a parameter quantifying the thrust loss due to propeller/nozzle – hull interaction. The thrust loss at bollard pull amounts to about 4%-12% and strongly depends on the propeller loading, propulsion system configuration and the form of the hull lines (especially buttock lines) at the aft end of the ship. Given the scale ratio of the model  $\lambda$ , the full scale BP, propeller revolutions and power can be calculated using:

$$T_{BP(S)} = \frac{\rho_S}{\rho_M} * \lambda^3 * T_{BP(M)} \quad (2)$$

Where indexes  $s$  and  $M$  refer to ship and model respectively.  $\rho_s$  and  $\rho_M$  are mass densities for salt and fresh water.

$$RPM_{(S)} = \frac{RPM_{(M)}}{\sqrt{\lambda}} \quad (3)$$

and

$$P_D = \frac{\rho_s}{\rho_M} * \lambda^{3.5} * 2 * \pi * \frac{RPM_{(M)}}{60} * Q_M \quad (4)$$

Typically the bollard pull test is conducted as a part of the self-propulsion test, as the ship model, propulsion system, measuring equipment and instrumentation is usually the same as those for the self-propulsion test. However, the bollard pull test can be distinguished from the ordinary self-propulsion test by a few major differences:

- The bollard pull test is conducted at zero speed of advance;
- The concepts of wake and relative rotative efficiency are no more applicable in bollard pull condition, whereas the interaction with the hull is accounted for by the familiar thrust deduction coefficient as discussed above. This also implies that the propeller open water characteristics are not necessarily required for the analysis;
- At bollard pull condition, the propeller induces very high axial and tangential velocities and actually acts as an axial pump. The flow through propeller disc is accelerated and creates a current in the towing tank, depending on its dimensions and the longitudinal position of the ship model/propeller relative to the tank length;
- Due to the heavy loading and induced axial and tangential velocities in the propeller slip stream, there is relatively strong interaction between the propeller and rudder, which will be discussed further in the text;
- At some conditions with very high loading, the propeller blades may start to ventilate due to air suction from free surface. This will significantly affect thrust and torque measurements. Furthermore, possible propeller cavitation and its influence on bollard pull performance cannot be modeled in a standard atmospheric pressure tank.

When conducting the bollard pull tests in the towing tank, special care is taken to avoid or minimize the negative effect of some of the above peculiarities. Thus the ship model is located approximately at the middle (length-wise) of the tank to minimize effect of propeller induced current and not to obstruct the propeller slip stream; sufficient waiting time between the measurements with variable RPM is allowed for the induced current to die out; the tests are normally conducted with RPM variation from the lowest to highest value, thereby inducing less axial velocity and weaker current; the bollard pull tests could be supplemented with parallel measurements of the induced current flow (current-meter).

### 3.2.1 Test Results with Stock Propeller/Nozzle System

The tests were conducted in the deep water towing tank at Force Technology, Denmark.

At this phase two types of nozzle support were tested; strut support and head-box support as shown in figure 4. Furthermore the influence of the propeller direction of rotation was studied. The results with regard to support type are presented in table 2.

**Table 2:** *Bollard and thrust deduction comparison versus nozzle support type*

Support type		Head-box	Strut
BP	[Tons]	109.2	113.1
t	[-]	0.061	0.089

As seen the better results were obtained with the strut support, despite the lower thrust deduction for the head-box version. The drop in BP for the head-box support could be explained with somewhat reduced effective surface of the nozzle, as a greater part (compared to the strut version) is buried in the head-box, hence reduced nozzle thrust. Considering that the nozzle could provide about 50% of the total thrust at bollard pull, the subject thrust degradation could be significant. Therefore, possible head-box nozzle support solutions should be applied with due consideration of minimizing the effective area loss.

**Table 3:** *Bollard and thrust deduction comparison versus propeller direction of rotation*

Direction of rotation		Inwards	Outwards
BP	[Tons]	113.1	115.3
t	[-]	0.089	0.069

Although operating at zero speed of advance, the propeller direction of rotation seems to affect the bollard pull. Bollard gain of about 1.9% was achieved with outward rotation, associated with thrust deduction reduction. A possible explanation of this effect could be a better interaction with the rudder associated with a better gain from tangential induced velocities recovery. This issue will be commented in more detail further in the text.

### 3.2.2 Test Results with Final Propeller/Nozzle System

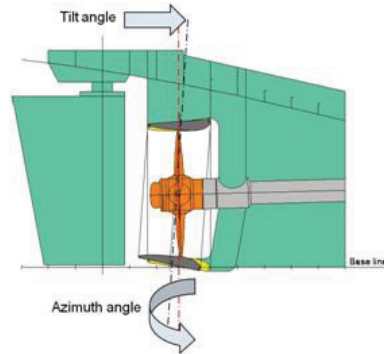
The bollard pull tests were conducted with the final MAN Diesel design of the ducted propeller system (propeller plus AHT nozzle). Use was made of the strut type nozzle support which was found more effective from the stock propeller tests phase. Furthermore, the clear effect of the AHT nozzle design was investigated by conducting bollard pull tests with the AHT nozzle combined with the stock propeller model. The results are summarized in table 4.

**Table 4:** *Bollard and thrust deduction comparison for stock and final designed propeller and nozzle*

Propeller		Stock	Stock	Final
Nozzle type		NSMB19A	AHT	AHT
BP	[Tons]	115.3	121.8	121.8
t	[-]	0.069	0.076	0.096

The bollard pull was increased with about 5.6% mainly due to the AHT nozzle contribution. As seen from table 4, the bollard pull for the stock propeller/AHT and final propeller/AHT nozzle combinations was practically found equal. This is because the stock propeller was not designed considering the cavitation performance.

The subject vessel was characterized with rather steep buttock lines, contributing to somewhat oblique propeller induced inflow. Therefore it was decided to experimentally investigate the effect of tilting the nozzle down (upper sections forward) as shown in figure 6.



**Figure 6:** *Definition of tilt and azimuth angles*

The idea was to achieve a more even and perpendicular inflow to the nozzle, as well as improved propeller and nozzle / rudder interaction. The geometrical parameters to be investigated at this stage were the tilt and azimuth angle variation of the nozzle. Note that the propeller position was kept unchanged during these variations; therefore the feasible tilt and azimuth angles were somewhat limited to a few degrees only due to propeller blade tip/nozzle/rudder clearance constraints. Azimuthing the nozzle at 1 deg toe-out resulted in insignificant change of the bollard pull. Therefore, the influence of the tilt angle variation was somewhat more pronounced. The results are summarized in the following table 5.

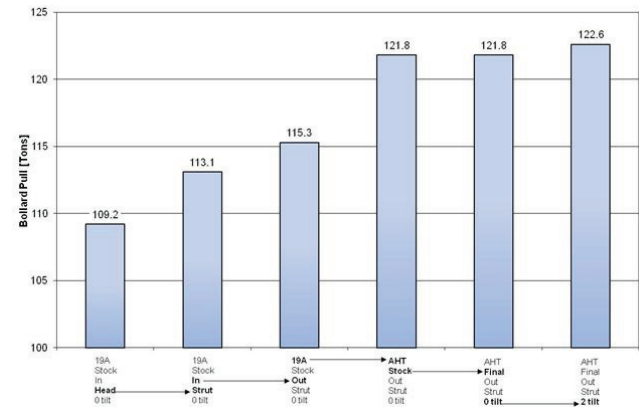
**Table 5:** *Bollard pull and thrust deduction comparison versus nozzle tilt angle*

Tilt angle		0 deg	2 deg	4 deg
BP	[Tons]	121.8	122.6	123.2
t	[-]	0.096	0.094	0.083
Improvement	[%]	0	0.6	1.1

As seen from table 5, tilting the nozzle up to 4 deg down leads to about 1% increase of the bollard pull with

associated reduction of the thruster deduction coefficient. Better results could probably be achieved with combined tilting of the propeller plane as well, but this option is practically very limited due to shaft line/engine arrangement constraints. Tilt angle optimization is a common practice though for azimuthing thruster and/or pod propulsion units. Despite the fact that a 4 degree tilt resulted in a marginally higher bollard pull it was for practical reasons decided to go with the 2 degrees tilt solution for the final propulsive system installation.

In summary, after the experimental investigation of the effect of varying relevant design parameters such as nozzle support type, propeller turning direction, propeller and nozzle design, nozzle tilting, the bollard pull for the subject vessel was predicted to increase from 109.2 tons to 122.6 tons, i.e. an increase of 12.3%. A summary of the tank test results can be seen in figure 7.



**Figure 7:** *Summary of the tank test results*

The predicted BP was later confirmed by full scale measurement as presented in the following table.

**Table 6:** *Measured Bollard pull for a series of sister ships of the subject project at sea trial*

Vessel No	Measured BP [tons]
1	124.0
2	121.7
3	122.2
4	121.2
5	122.5

The varying results are caused by different weather and sea conditions during testing. Even though all test were carried out according to an internal MAN Diesel standard (Boesen 2005) the water depth was restricted at the test site and furthermore influenced by a strong current on some of the measurements. The presented results are raw measurements without correction for water depth and current. Therefore the full scale results are considered conservative.

MAN Diesel experience indicates that full scale bollard pull tests show 2-3 % higher BP than predicted as based on model tests. Had the results being corrected for the non optimum environmental conditions the agreement between model and expected full scale results would have been better.

Therefore the presented design approach and model test predictions were verified by the full scale results.

### 3.2.3 Propeller Rudder Interaction Issues

The tangential and axial velocities induced in the flow by the operating propeller alter the speed and incidence of the inflow to the rudder. This controls the forces and moments acting on the rudder. The rudder itself both blocks and diverts (at non-zero rudder angle) the upstream flow onto and through the propeller disc, which in turn affects the thrust and torque of the propeller. The average flow generated by the propeller has axial and swirl components. The accelerated axial component increases the inflow onto the rudder and thereby its frictional drag. The net effect of the swirl is an effective shift in local rudder incidence in one direction above the propeller axis and in the opposite direction below the axis. With high propeller thrust loadings, such as the case of bollard pull, the induced angles can become large and the flow is vectored onto the rudder in such a way that the drag may become negative, or a thrust is produced by the rudder. As illustrated by Molland & Turnock (2007), the propeller induced velocities, arriving at the rudder is a function of the propeller thrust loading  $K_T/J^2$  (or thrust per unit area) and distance X between the propeller and rudder.

The rudder effect on the bollard pull was additionally investigated by conducting an experiment with the rudder removed. The comparison results are presented in figure 8 as function of total propeller power as well as propeller revolutions.

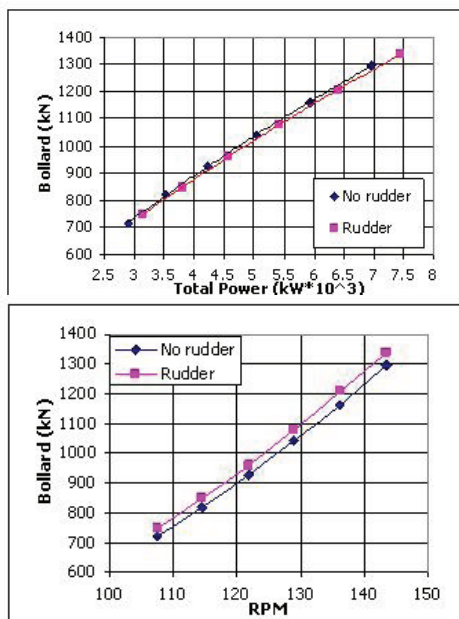


Figure 8: Effect of rudder on bollard pull

At equal power consumption the bollard pull without the rudder was marginally larger, which indicated that the net forces on the rudder were dominated by the drag. On the other hand, if the bollard pull is compared at equal propeller revolutions, it appeared that the rudder existence contributed to a significantly larger bollard pull, but at the expense of larger power consumption. This means that the rudder influenced in turn the inflow to the propeller, as discussed above, which resulted in increased propeller torque. Therefore, the rudder configuration and its location to the propeller/nozzle complex could be an effective design tool for further bollard pull optimization. Twisted rudder sections (above and below the propeller axis); small horizontal fins on the rudder (at propeller axis level); Costa-bulb on the rudder, etc. are commonly used energy saving devices for optimization of the ships propulsive performance at speed, but could be further explored as an effective design tool for bollard pull optimization.

### CONCLUSIONS

The combination of specially designed propeller and high thrust nozzle for the presented case study allowed achieving 13% increase of the bollard pull in model scale compared to the stock propeller/nozzle case, meeting also the transit speed/power requirements. Full scale results were found in full agreement with the predicted BP values from model test results.

Application of CFD optimization studies and simulations proved very efficient and significantly reduced the number of geometrical design options to be tested.

The close cooperation between propeller designer and model test facility accomplished during the presented design and testing process proved to be very effective and feasible for the successive achievement of the design criteria. Furthermore, the authors consider it very important and strongly recommend that the owner, hull designer and rudder supplier are also more closely involved into this process.

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